A CASE FOR WASTE FRAUD AND ABUSE: STOPPING THE AIR FORCE FROM PURCHASING SPACECRAFT THAT FAIL PREMATURELY

Len Losik, Ph.D
Failure Analysis

ABSTRACT

Spacecraft and launch vehicle reliability is dominated by premature equipment failures and surprise equipment failures that increase risk and decrease safety, mission assurance and effectiveness. Large, complex aerospace systems such as aircraft, launch vehicle and satellites are first subjected to most exhaustive and comprehensive acceptance testing program used in any industry and yet suffer from the highest premature failure rates. Desired/required spacecraft equipment performance is confirmed during factory testing using telemetry, however equipment mission life requirement is not measured but calculated manually and so the equipment that will fail prematurely are not identified and replaced before use. Spacecraft equipment mission-life is not measured and confirmed before launch as performance is but calculated using stochastic equations from probability reliability analysis engineering standards such as MIL STD 217. The change in the engineering practices used to manufacture and test spacecraft necessary to identify the equipment that will fail prematurely include using a prognostic and health management (PHM) program. A PHM includes using predictive algorithms to convert equipment telemetry into a measurement of equipment remaining usable life. A PHM makes the generation, collection, storage and engineering and scientific analysis of equipment performance data "mission critical" rather than just nice-to-have engineering information.

KEY WORDS

Telemetry, Prognostic, Failure Prediction, Failure Analysis, Diagnostic, Satellite Failure, Launch Vehicle Failure, Failure Analysis, Prognostic Analysis

INTRODUCTION

System and equipment mission life became overly important in the production of ICBM's in the early 1950's because ICBM's failed prematurely so often. The ICBM effort was contractor driven because the military had few personnel with experience in ICBM design and test. The main branch of the military in the 1950's was the combined Army-Air Force who had fought and won World War I and World War II. The jet age and ICBM era stretched the Army-Air Force resources. The process that was developed to increase the reliability of U.S. ICBMs was adopted to produce equipment across a wide variety of industries.

[1] Jet aircraft are designed to be serviceable by maintenance personnel, but ICBM's and spacecraft are not serviceable and so have only one chance of getting it right and failed prematurely

regularly. Each time an ICBM failed in development and test, the Army-Air Force would purchase 50 or 100 more just to ensure that more were available than previously. For ICBM's and later launch vehicles and satellites, equipment mission life became an important requirement that contractors were forced to meet using PRA.

TABLE 1 SUMMARY OF RESULTS FROM AEROSPACE CORPORATION STUDY TO DETERMINE EFFECTIVENESS OF TESTING SATELLITE EQUIPMENT BEFORE LAUNCH

		[2] Number of Equipment Failures per Dynamic Environmental Acceptance Test							
Space Command /Air Force Satellite Program Name	**No. of Satellites Tested per Program**	**Acoustic**	**Thermal Cycling**	**Acoustic**	**Thermal Vacuum**	**Thermal Cycling**	**Acoustic**	**No. of Satellites in Followed to Space**	**No. of Surprise Equipment Failure within 45 Days On-Orbit**
E2	4	--	5.5	--	2.8	--	0.5	4	0.5
D1*	3	0.3	--	--	1.7	--	--	3	2.0
D2*	1	0	2.0	--	2.0	--	--	1	1.0
D3*	9	0.9	1.4	--	1.6	--	--	7	0.6
D4/D5*	2	0.5	1.5	--	0	--	--	1	0
B	16	0.6	--	--	1.2	--	--	11	0.6
G	4	1.0	--	--	3.8	--	--	3	2.0
F1	5	--	1.0	0.4	0.4	--	--	4	0.3
F2	3	--	4.3**	0.7	1.3	--	--	1	0
H1	2	0.5	--	--	5.5	--	--	2	1.0
H2a	1	2.0	--	--	2.0	6.0	--	1	1.0
H2b	2	0.5	--	--	3	9.0	--	2	0.5
C	8	1.1	--	--	3.0	--	--	7	0.5
Total:	**60**	**7.4**	**15.7**	**1.1**	**28.3**	**15.0**	**0.5**	**47**	**18**
Weighted Average				**4.0**				**0.7**	

*Spacecraft only, ** Pre-environmental functional part of thermal vacuum [2]

Since equipment failed prematurely and the premature failures could not be stopped, the likelihood that the mission life could be achieved was increased by providing redundant equipment for use in the event a failure occurred. Since premature failures could not be stopped but compensated for buying many more than needed, probability reliability analysis was added so that contractors could calculate the likelihood of the mission life being achieved.

FACTORY ACCEPTANCE TESTING PROGRAMS USING TELEMETRY

In the late 1950's U.S., missile and launch vehicle reliability continued to suffer, often achieving only 50% reliability. To improve equipment reliability, the U.S. government and industry agreed to expose the on-board equipment the launch environment believed to occur before delivery for use. This was done to identify and repair/replace/salvage/scrap any equipment that did not survive these conditions. The hope was that the surviving equipment after dynamic environmental acceptance testing would be higher than if the equipment had not been exposed to the extreme conditions. Equipment performance is measured and confirmed before, during and after testing is completed, usually by analyzing equipment telemetry. Since telemetry is an overhead cost, less than 95% of the equipment will have telemetry data available from test. Since equipment performance data is the only measurement that is made during dynamic environmental factory acceptance testing, and performance is unrelated to equipment usable life, the reliability of equipment subjected to factory dynamic environmental acceptance testing is dominated by premature failures.

[3] Dynamic environmental acceptance testing is performed at varying magnitudes and durations to verify the design of complex space systems will function to performance specifications when it arrives in space meet equipment performance specifications during its entire planned mission life and to screen flight hardware and verify the quality of workmanship meets industry standards. The first step in this process is the definition of the maximum expected environments during launch and on-orbit operation. Data from previous flights and ground tests are analyzed to generate predictions for a specific mission. This information is used in the stochastic equations in a reliability analysis engineering required completed by the procurement contract. These environments are then flowed down from the space vehicle level to the various subsystems and components for use as design requirements and, later, as test requirements.

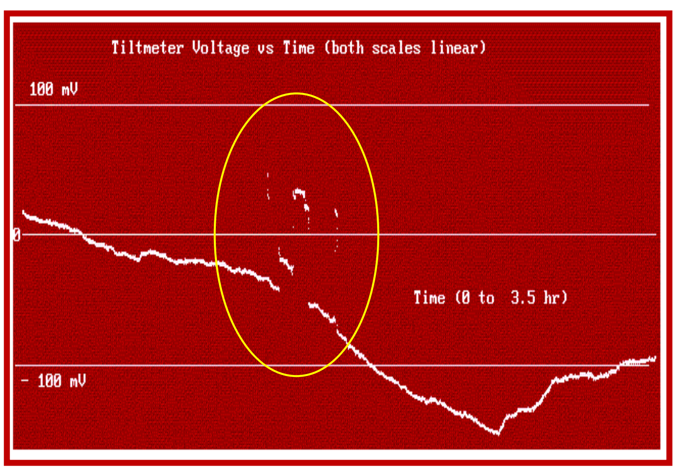


FIGURE 1 EXAMPLE OF THE TRANSIENT BEHAVIOR IN EQUIPMENT TELEMETRY CAUSED FROM ACCELERATED AGING DIAGNOSED AS NOISE

Contracts for spacecraft and launch vehicles include a financial penalty for missing the delivery date but do not include a financial penalty for a premature failure. Financial incentives may be lost but there will be no out-of-pocket financial losses. The contract for spacecraft was developed because equipment was failed prematurely and they could not be stopped and test equipment and software was the source of most transients. This may motivate companies to misdiagnose all transient events as noise so that the test schedule will not be slowed from searching for the sources of transient behavior. Today, the huge increase in processing speed decreases the likelihood of transients occurring from test equipment so that transients that occur are from the equipment under test.

EQUIPMENT PERFORMANCE MEASURING AND CONFIRMATION USING TELEMETRY

Equipment and vehicle performance requirements are included in procurement contracts for all aerospace and defense equipment. Equipment performance requirements will define how well equipment must function. When equipment is designed, it is designed to meet specific performance requirements. To ensure that equipment meets or exceeds its performance requirements, the performance requirements are confirmed during the final factory testing programs called acceptance test program or ATP. When equipment does not meet or exceed its performance requirements, it is repaired and/or replaced. Some equipment fails several times during the ATP. It is repaired each time in violation of PRA. If equipment fails five or more times, material control personnel will scrap the equipment and replace it, saying that its reliability is too low.

MEASURING AND CONFIRMING EQUIPMENT REMAINING USABLE LIFE/MISSION LIFE

When reliability is defined as a likelihood of occurring, the behavior it quantifies is assumed instantaneous and random whether the behavior is or not. This is having the Markov property and having the Markov property is the basis for many of the stochastic equations used in defining equipment needs and serviceability requirements. [3] Do equipment failures occur instantaneously and random? No. Although equipment may exceed its performance specification or stop using electrical power quickly, the process of failing began many weeks or months prior to the event. The equipment began to fail the first time electrical power was applied or the mechanism was used for the first time.

[4] Parts degrade in performance starting at beginning of life when power is first applied. When one part starts to degrade in performance much faster than the others, the part is suffering from accelerated aging. Accelerated aging is also the term we use to define to exposing parts or equipment to higher operating temperatures so that parts will degrade much faster. Accelerated aging occurs when at least one part in a circuit or mechanical assembly degrades in performance faster and causes non-repeatable, unique transient events. When telemetry is available from either electrical or mechanical equipment, the non-repeatable transients are visible when the behavior is processed using predictive algorithms. [6] Telemetry provides performance information. Predictive algorithms convert time series telemetry into a measure of equipment life. Data-driven predictive algorithms convert equipment performance information (e.g. volts,

amps) into a measurement of remaining usable life. Integrating this function probability distribution function yields the cumulative distribution function.

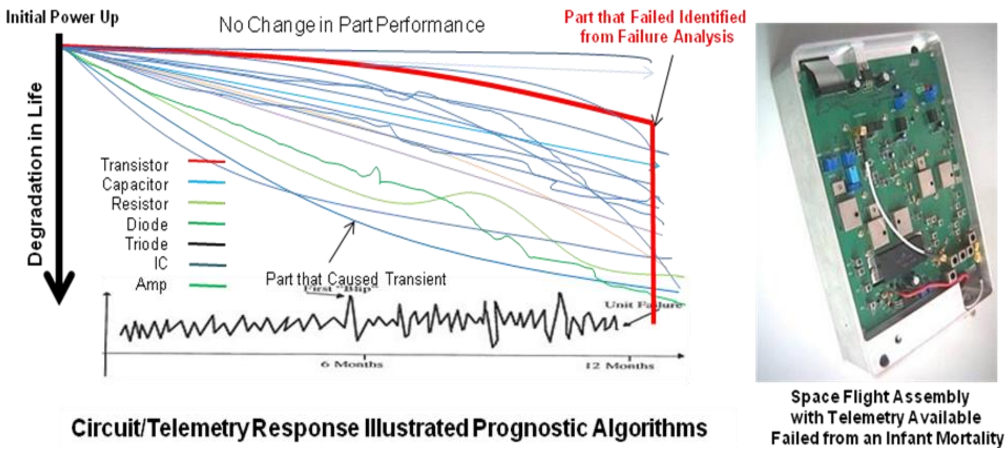


FIGURE 2 THE REASON PREDICTIVE ALGORITHMS CAN MEASURE EQUIPMENT USABLE LIFE USING EQUIPMENT TELEMETRY

TT&C Subsystem Test Plan	Fully Functional	Abbreviated Functional	Random Vibration	Pyro Shock	Thermal Cycling	Thermal Vacuum	EMI/EMC
Command Functional	X	X	X	X	X	X	X
Input Signal Reference	X	X					
Output Signal	X	X	X				
On/Off Telemetry	X	X	X	X	X	X	X
Ranging Loop Stress	X	X					
Output RF Power	X	X					
5 Volt Telemetry Calibration	X	X	X	X	X	X	X
15 Volt Telemetry Calibration	X	X	X	X	X	X	X
IF Carrier Frequency	X						
Phase Noise	X						
Bit Error Rate	X	X	X	X	X	X	X
RF Output Power	X	X					
Spurious and Harmonic Output	X						
Output Power	X						
Inrush Power	X						
Input Voltage	X	X	X	X	X	X	X
Under voltage	X						
Overvoltage	X						

TABLE 2 EXAMPLE OF A SATELLITE TT&C SUBSYSTEM DYNAMIC ENVIRONMENTAL ATP TEST PLAN

PROGNOSTIC ANALYSIS

The scientific analysis, training and tools used to conduct a prognostic analysis that will illustrate and identify the early signs of premature aging/failure (a.k.a. accelerated aging) are used in a prognostic analysis. Prognostic technology accepts that equipment failures do not have the Markov property and that accelerated aging exists and will identify the equipment that will fail prematurely within one year of use.

Key to predicting equipment remaining usable life is the availability of telemetry or any other performance data. [5] Telemetry was adopted for use on spacecraft from the jet-aircraft flight test community in the late 1950's at Edwards Air Force Base. Equipment analog telemetry was developed to retrieve jet aircraft equipment performance information from aircraft equipment in the event the pilot died in a crash before a debriefing occurred.

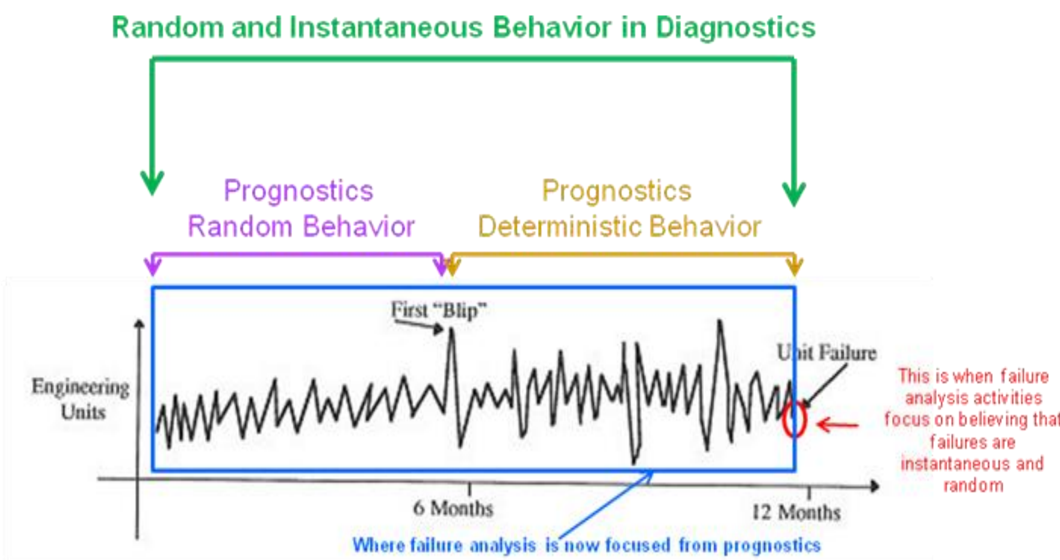


FIGURE 3 COMPARISONS BETWEEN DURATION BETWEEN EQUIPMENT BEGINNING-OF-LIFE AND END-OF-LIFE BASED ON DIAGNOSTIC ANALYSIS AND PROGNOSTIC ANALYSIS.

A prognostic analysis is a forensic analysis, which includes but is not limited to using operating equipment analog data and proprietary, data-driven or model-based algorithms to illustrate accelerated aging in test data or data of any kind. Accelerated aging is observable as latent, transient behavior among other normal transient behavior. Personnel must receive special training (prognostician) to discriminate transient, deterministic (predictable) behavior from other expected transient behavior. In complex systems such as a satellite/launch vehicle, the operational environment of the on-board equipment is very dynamic. Equipment may be cycling or set to cycle and thus the behavior of the equipment telemetry may include transient behavior as a result. Prognosticians must be able to discriminate between normal occurring transient behavior and accelerated aging.

A prognostic analysis can use existing and archived equipment analog telemetry, which is also used to measure equipment performance during test and during launch. Telemetry is sampled analog data that is often available from aerospace equipment in many forms and states. Satellite/launch vehicle equipment often has telemetry available, but often not all equipment provides telemetry. Telemetry is not paid for as a separately item and contractors decide which equipment provides telemetry

Satellite/launch vehicle equipment that is going to fail during launch will have deterministic behavior present in telemetry, when telemetry is available, which can be illustrated using data-driven prognostic algorithms and identified by personnel trained to discriminate the transient behavior from other normal occurring transient behavior (prognosticians) in a prognostic analysis. Telemetry is not always available from all equipment and so a prognostic analysis may be done on equipment that does not have telemetry available during I&T. Data from test equipment may be used if it has been archived. Generally, test equipment data is not archived during equipment trouble shooting activities.

PROGNOSTIC TECHNOLOGY

Prognostic technology includes pro-active diagnostics, active reasoning and model-based and data-driven prognostic algorithms. The algorithms can work in a full noise environment for illustrating accelerated aging and explain equipment failures are a combination of random and deterministic behavior. Prognostic technology includes the use of predictive algorithms for illustrating the deterministic information, often present in normal appearing data from equipment that is operating normally that prognosticians use to identify piece-parts and assemblies that have failed, is failing and will fail in the near future.

[6] Model-based prognostic algorithms incorporates failure models of the system into the estimation of remaining useful life (RUL) and so are well suited for pattern recognition systems. Data-driven algorithms use existing operational data to determine normal behavior and discriminate normal from the early signs of premature aging/failure. In the satellite/launch vehicle environments, signal line noise may be present caused from degradation in Eb/No, RF noise from a variety of sources as well as equipment noise that generates the data used to conduct a prognostic analysis may be present and the prognostic algorithms must be able to identify, remove/replace this data.

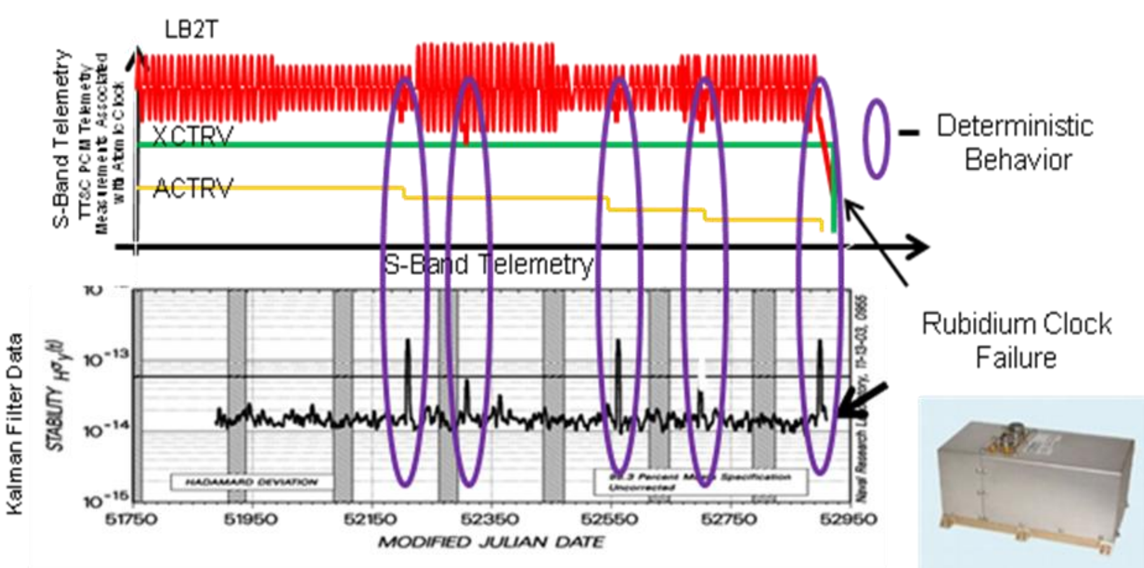
WHAT IS A PREDICTIVE ALGORITHM?

The Markov property is named for a Russian mathematician and is defined solely of random and instantaneous behavior. The Markov property is a fundamental assumption in reliability analysis so that stochastic processes can quantify parts, equipment, systems, processes and software reliability in probabilistic values. Due to the wide spread use of reliability analysis engineering results in the aerospace industry, engineers may have come to believe that equipment failures really are instantaneous and random and thus cannot be predicted or prevented.

A predictive algorithm includes a series of actions, including a scientific analysis, taken by personnel trained to prevent surprise failures from occurring. Using diagnostic analysis, personnel are trained to react with a diagnostic analysis after a failure occurs. Changing the paradigm from reaction to prevention requires training in completing a scientific analysis. Predictive algorithms simply relate past equipment, non-repeatable transient events that is identifiable in equipment engineering test data with equipment end of life. These actions use the same engineering data used to complete a diagnostic analysis to confirm equipment performance but uses predictive algorithms to convert equipment analog telemetry (performance measurements) into a measurement of unit remaining usable life.

A diagnostic analysis looks backward in time to determine past equipment behavior. A prognostic analysis looks back in time to predict future equipment behavior. A scientific analysis is necessary because the results from an engineering analysis only provide diagnostic information. The results from a diagnostic analysis cannot be used to measure equipment remaining usable life. A scientific (prognostic) analysis is completed on the results from diagnostic analysis.

[7] Predictive algorithms illustrate the presence of accelerated aging that is often identifiable in normal appearing data from fully functional equipment that will fail prematurely. Predictive algorithms offer spacecraft purchasers and spacecraft builders the tools necessary to purchase satellites and launch vehicle services that will not fail prematurely and suffer from surprise on-orbit failures. Using predictive algorithms and prognostic analysis, contractors and mission control personnel will identify the equipment that will fail prematurely (and predict when satellite subsystem equipment will fail).



Master Control Station Kalman Filter data

FIGURE 4 THE PROGNOSTIC ANALYSIS COMPLETED ON AN AIR FORCE GPS BLOCK I ON-ORBIT SATELLITE RUBIDIUM ATOMIC FREQUENCY STANDARD

CALCULATING REMAINING USABLE LIFE (RUL)/TIME TO FAILURE (TTF)

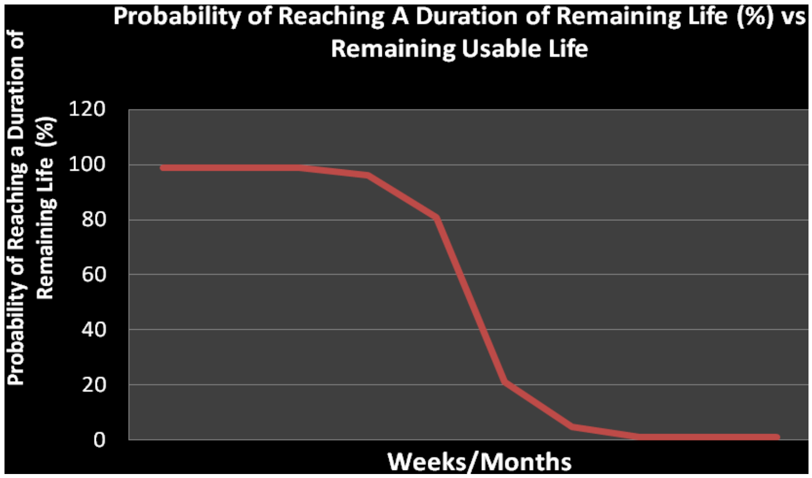


FIGURE 5 PROPRIETARY CUMULATIVE DISTRIBUTION FUNCTION USED TO DETERMINE EQUIPMENT TIME-TO-FAILURE/REMAINING-USABLE-LIFE USING ANALOG TELEMETRY

Equipment with accelerated aging will fail prematurely with 10% certainty. Calculating remaining usable is a proprietary process and may be unique for each company/organization. The remaining-usable-life or the time-to-failure (TTF) for equipment can be calculated once accelerated aging has been identified by using the piece-part failure characteristics in equipment telemetry generated under test. The duration of remaining life is then determined from duration of remaining usable life that occurred on other equipment. The proprietary cumulative distribution curve is used to determine the likelihood of meeting a desired duration of remaining usable life.

CONCLUSION

It is possible to use engineering practices that allow the production of spacecraft equipment that meet performance requirements and mission life by measuring equipment performance during dynamic environmental acceptance testing and using telemetry and predictive algorithms. Equipment life can be measured by converting equipment analog telemetry into a measurement of mission life by identifying accelerated aging using predictive algorithms. Only measuring and confirming equipment performance just prior to delivery results in producing equipment with reliability that is dominated by premature and surprise equipment failures. Failures often remove equipment and space systems from service. With procurement contracts including a financial penalty only for late delivery, it became advantageous to overlook all equipment under test transient behavior in test data to minimize risk in missing the delivery date. With the gigantic advancement of processor processing speed and stable test equipment and software, the transient behavior in test data can be associated with equipment end of life. Since equipment performance is unrelated to equipment usable life, a measurement of equipment life should be made before shipping equipment to a customer. A prognostic analysis uses predictive algorithms to convert analog equipment telemetry of any type to a measurement of equipment remaining usable life. Equipment with accelerated aging will fail prematurely with 100% certainty. Measuring equipment remaining usable life after confirming performance will allow the production of equipment that will not fail prematurely.

REFERENCES

1. Losik, Len, Upgrading the Space Flight Factory Acceptance Testing for Equipment and Space Vehicle Design, Manufacture, Test and Integration, AIAA Space 2009 Conference proceedings.
2. Tosney, William, Pavlica, Steven, Crosslink, Aerospace Corporation's Magazine of Advances in Aerospace Technology, fall, 2005 issue, pages 6-10.
3. Markov Modeling for Reliability, www.mathpages.com/home/kmath232/part 1/part 1.htm
4. Losik, Len, Predicting Hardware Failures and Estimating Remaining-Usable-life from Telemetry, SanLen Publishing, Sacramento, CA, 2004, ISBN 978-0-9767491-9-6
5. Failure Analysis, Satellite and Launch Vehicle Prognostic Algorithms Users Guide, V2.9
6. Losik, Len, Wahl, Sheila, Lewis, Owen, "Predicting Hardware Failures and Estimating Remaining-Usable Life from Telemetry", Lockheed Martin Space Systems Company, Proceedings from the International Telemetry Conference, Las Vegas, NV, October, 1996
7. Cheng, Shunfeng and Pecht, Michael, Multivariate State Estimation Technique for Remaining Usable Life Prediction of Electronic Products, Association for the Advancement of Artificial Intelligence, CALCE, 2007.